THE UNIVERSITY OF ALBERTA

I. A QUANTITATIVE STUDY OF THE ENERGIES OF SINGLE ALPHA PARTICLES FROM THE PHOTONUCLEAR REACTIONS OF SILVER AND BROMINE NUCLEI

AND

II. A QUALITATIVE STUDY OF MULTIPLE ALPHA EVENTS INDUCED BY PHOTONUCLEAR REACTIONS OF CARBON, NITROGEN AND OXYGEN NUCLEI

A DISSERTATION

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ABSTRACT

An Ilford El nuclear research emulsion was exposed to 600 roentgens of bremsstrahlung from the University of Saskatchewan betatron at maximum betatron energy 24 Mev. The plate was developed by a grain-gradation process in order to suppress proton tracks and background fog. The double-peaked single alpha particle energy spectrum resulting from the photo-disintegration of silver and bromine nuclei was studied. Interpretations of the energy spectrum of these events were deduced. Multiple-alpha events induced by photonuclear reactions of carbon, nitrogen and oxygen nuclei were also studied.

INTRODUCTION

Photonuclear reactions which involve the emission of particles from the nuclei provide a method for studying nuclear structure. Nuclear research emulsions exposed in ~~the~~ a beam of the gamma-rays have shown tracks of alpha particles resulting from the photo-disintegration of nuclei present in emulsions. The nuclear events observed in an emulsion can be grouped according to the number of tracks which the emitted alpha particles have left in the emulsion.

1. Single Track Events.

Most of these events are attributed to alpha particles resulting from the photo-disintegration of silver and bromine in nuclear emulsions. Nabholz, Stoll and Waeffler at Zurich (1), working with 17.6 Mev Lithium gamma-rays, have reported work on these events.

The energy spectrum of single alpha particles exhibits a characteristic double peak. A typical spectrum (Fig. Ia) shows two energy peaks. Haslam and co-workers at the University of Saskatchewan (2), and Millar and Cameron (3), interpreted the energy distribution in terms of the statistical theory of photonuclear reactions and attributed the higher energy peak to parallel and cascade photo-alpha reactions of the types (γ, α) and $(\gamma, \alpha n)$ in silver and bromine, and the lower energy peak to threshold-favored alpha particle emissions in reactions of the types $(\gamma, n\alpha)$, $(\gamma, p\alpha)$ and $(\gamma, \gamma'\alpha)$.

Greenberg (5), while working at the University of Saskatchewan, obtained a slightly different pattern of the energy spectrum of single alpha particles, which showed statistically small but definite maxima in the region above 6 Mev, between the two characteristic peaks. One would not expect such

maxima from alpha particles originating in silver and bromine. However, if these maxima do exist, they could be due to alpha particles arising in the nuclei of light elements such as carbon, nitrogen and oxygen. Moreover, in this case, it is probable that at least a small fraction of the high-energy peak is due to alpha particles originating in a light nucleus. Also most of the low-energy peak may perhaps be attributed to a (γ,α) reaction in a light nucleus.

The main purpose of this project has been to resolve these secondary maxima as reported by Greenberg. For this purpose 2693 single alpha particle tracks have been measured. An attempt was made to interpret the energy spectrum in terms of the statistical theory of nuclear reactions.

2. Two-Track Events.

These are events occurring in light nuclei. These events have been reported and interpreted as the reactions $N^{14}(\gamma,\alpha)B^{10}$, $O^{16}(\gamma,\alpha)C^{12}$ and $C^{13}(\gamma,\alpha)Be^{9}$ by Millar and Cameron (6). An alpha particle ejected from a light nucleus gives a considerable amount of energy to the recoiling nucleus. In many cases the track of the recoil nucleus is visible, as a short, densely-ionized stub at the beginning of the alpha particle track.

In the case of a carbon nucleus emitting an alpha particle another possible reaction is $C^{12}(\gamma,\alpha)Be^{8}$. However, this interpretation of the observed events is considered unfavorable in view of the lifetime of Be^{8} (3).

3. Three-Track Events.

These events occur mainly in C^{12}. The most probable reactions by which the C^{12} nucleus might break into three-pronged alpha particle stars are

(a) $C^{12}(\gamma, 3\alpha)$

(b) $C^{12}(\gamma, \alpha) Be^8$; $Be^8 \rightarrow 2 He^4$

(c) $C^{12}(\gamma, \alpha) Be^{8*}$; $Be^{8*} \rightarrow 2 He^4$

Since Haenni et al. (7) originally interpreted these events as proceeding through the excited state of Be^8, i.e., the reaction (c), the interpretation of these events has been confirmed and identified by many workers, such as Teledgi and Eder (8), Goward and Wilkins (7), and Millar and Cameron (3). If the events show a momentum balance, the reaction is of the type (a). The events due to the reactions (b) and (c) have a long single alpha particle track with a narrow V formed by the Be^8 or Be^{8*} nucleus break-up.

Greenberg (5) located a fairly large number of the events due to the reaction type (b) and is presently examining the angular distribution of the first-emitted alpha particle tracks to determine the spin of Be^8.

There are the events which do not show a momentum balance among three α prongs. These events have been identified as due to the reaction $N^{14}(\gamma, Li^6)2He^4$ by Wilkins and Goward (10).

Besides the above events, the reported three track events are

$C^{13}(\gamma, 2\alpha)He^5$ (5),

Ag $(\gamma, 2\alpha)$Ru (11) (identity uncertain), $(Ru \xrightarrow{\beta} Tc)$

Ag $(\gamma, 2\alpha)$Tc (3) (identity uncertain).

4. <u>Four-Track Events.</u>

These events occur in oxygen. Goward and Wilkins (12) attributed the majority of the cases to the reactions $O^{16}(\gamma, 4\alpha)$ and $O^{16}(\gamma, 2He^4)Be^8$;

$Be^8 \rightarrow 2\,He^4$. Other possible processes in oxygen are

(a) $O^{16}(\gamma, 2Be^8)$; $2\,Be^8 \rightarrow 4He^4$: Goward & Wilkins (13)

(b) $O^{16}(\gamma, 2Be^{8*})$; $2\,Be^{8*} \rightarrow 4\,He^4$

(c) $O^{16}(\gamma, 2\,He^4)Be^{8*}$; $Be^{8*} \rightarrow 2\,He^4$

(d) $O^{16}(\gamma, He^4)C^{12*}$; $C^{12*} \rightarrow He^4 + Be^{8*}$ $Be^{8*} \rightarrow 2\,He^4$

The problem remains to identify the exact mechanism of these reactions.

Goward (14) and Millar and Cameron (3) have reported events which are probably due to the reaction in nitrogen, $N^{14}(\gamma, D)3He^4$

THEORY

Photonuclear excitation of medium-heavy and heavy nuclei, including silver and bromine takes place usually by means of an electric dipole interaction between photons and nuclei (15). Such interaction may result principally in the direct excitation of a nuclear proton (16). If the proton fails to escape before the excitation energy is spread among the nucleons an excited compound nucleus is thereby formed.

1. Parallel and Cascade Photo-alpha Reactions.

When an excited compound nucleus decays initially by emission of a photon or one of several different particles, it is said that the different modes of decay are in parallel competition with one another. When the residual nucleus is left in an excited state further decay may occur by one of several modes. Then it is said that there is cascade competition between the modes of the first decay and the modes of the second decay.

The emission of alpha particles from the compound nucleus in parallel competition in a single decay is known to be greatly favored. According to the statistical theory of photonuclear reactions (4, 17), the energy distribution of alpha particles from a compound nucleus is

$$I(E_\alpha)dE_\alpha = \text{const.}\ E_\alpha\, \sigma_\alpha(E_\alpha)\quad \omega_R(\epsilon)\ dE_\alpha ,$$

where E_α is the alpha particle energy, $\sigma_\alpha(E_\alpha)$ is the cross section of the residual nucleus for capture of an alpha particle with energy E_α, and $\omega_R(\epsilon)$ is the level density of the residual nucleus at an energy ϵ. If the compound nucleus was excited by a photon of energy $h\nu$, then

$$\epsilon = h\nu - E_\alpha - Q_\alpha ,$$

where Q_α is the binding energy of the alpha particle in the original nucleus. Millar and Cameron (3) attributed the higher energy alpha

particle peak to such (γ, α) reactions in silver and bromine.

The residual nucleus will occasionally be left sufficiently excited to emit further particles after the emission of an alpha particle from the highly excited compound nucleus. Hence initial alpha particle emission may be followed by particle emission in cascade reactions of the types ($\gamma, \alpha n$), ($\gamma, \alpha\alpha$) and ($\gamma, \alpha p$). In the neighborhood of silver the binding energies of alpha particles, protons and neutrons are respectively 3, 7 and 9 Mev. When the excitation energy of the residual nucleus is less than 9 Mev it is not possible for a neutron to be emitted. In this case charged-particle emission may occur. Such events are said to be threshold-favored. They are discussed in the next section. The emission of neutrons will be more probable, since the secondary emission of a charged particle is impeded by the presence of the Coulomb barrier. Therefore, the reaction ($\gamma, \alpha n$) may also provide a main source of high energy alpha particles.

The emission of an alpha particle may occur in cascade reactions of the types ($\gamma, \gamma' \alpha$) and ($\gamma, \alpha \gamma'$). In such reactions initial photon absorption is followed by the electric dipole radiation of a low energy gamma-ray (18). Hence, these reactions will also provide a source of high energy alpha particles.

2. <u>Threshold-favored Alpha Particle Emission.</u>

In the special case where the residual excited nucleus emits a charged particle, the emission of such particles is termed threshold-favored. Halsam et al. (2) have explained the lower energy alpha particle peak in terms of threshold-favored alpha particle emission in silver and bromine. Cross sections for the nuclear absorption of photons of energy less than 10 Mev

are very small, so that reactions of any sort induced by photons of energy less than 10 Mev are not expected to be important. The probability of cascade events increases with increasing photon energy for energy above 10 Mev. The excited compound nucleus which has absorbed higher energy photons may decay initially by emission of a particle or a photon and leave the residual nucleus with an excitation in excess of the binding energy of an alpha particle but not of a proton or a neutron. Hence, in this case, the emission of an alpha particle is the only mode of de-excitation by which the residual nucleus may lose its energy of excitation. Low energy alpha particles may, therefore, be expected to be emitted in threshold-favored cascade reactions of the types ($\gamma, \gamma'\alpha$), ($\gamma, n\alpha$), ($\gamma, p\alpha$), and ($\gamma, \alpha\alpha$).

At low excitation energies only alpha particles and gamma-rays will be emitted from an intermediate residual nucleus. The emission of alpha particles will become more probable as the excitation energy is increased. But at excitation energies above 7 Mev protons can also be emitted and the alpha particle yield will be relatively reduced. At still higher energies, electric dipole radiation may lower the intermediate nuclear energy to the threshold-favored region. This may produce tertiary reactions of such types as ($\gamma, n\gamma'\alpha$), ($\gamma, p\gamma'\alpha$). It may be expected that threshold-favored alpha particle emission will be most probable when a residual nucleus is not quite sufficiently excited to emit a proton.

EXPERIMENTAL METHOD.

(The work of this project has been concerned with the examination of a plate already exposed and developed at Saskatoon. Comments on the exposure and development are included here for the sake of completeness).

1. Plate Irradiation.

Ilford type El nuclear emulsions, 1" x 3" were exposed to an irradiation corresponding to 600 roentgens of bremsstrahlung from the University of Saskatchewan betatron operating at maximum energy 24 Mev. To get significant data on the energy distribution of single alpha particle tracks as well as other events it is necessary to locate a very large number of events. Searching for the events is very time-consuming. An increase in the dose given to the plates in this experiment compared with other workers (2, 3) resulted in an increase in the density of events. After development an emulsion showed very distinct alpha particle tracks in a light background fog. The background fog is due to the secondary electrons from emulsion, film covering, air, donut wall, shield, etc. More radiation ~~can~~ could be put into the plates if the sources of the secondary electrons could be removed. Plates were exposed so that the direction of the beam was along the surface of the emulsion.

2. Plate Development.

Ilford type El nuclear emulsions are comparatively less sensitive to lightly-ionized particles such as protons or electrons and very sensitive for recording alpha particles of fairly low energy. The plates were developed in a modified Van der Grinten's grain gradation developer (26). This process suppressed secondary electron fog as well as proton tracks.

3. Plate Survey.

Among developed plates, a plate El(205) was selected and studied under a Bausch and Lomb binocular microscope with a nominal magnification of 1000 diameters. The plate showed alpha tracks very distinctly in the presence of the slight background fog. Faint lightly-ionized proton tracks were occasionally visible, but were easily distinguishable from alpha particles.

Total area of 1.65 cm.^{2} on the plate was searched. All the events observed were carefully located and recorded and the energies of all single alpha particle tracks were measured. To obtain the energies of the particles it is necessary to measure track lengths (Appendix I) and have knowledge of a range - energy relationship in the emulsion. Cameron, while working at Chalk River, calculated a range-energy relation for Ilford type El emulsions. (Table IV). As a result of work by numerous observers, for example (24), it is believed that this relation is valid within 2%.

During observation it was noticed that there were tracks which escaped from the emulsion and some tracks which ended within 2 microns of either surface of the emulsion and could not be distinguished from those which escaped. Therefore it was necessary to take into account an escape correction for the observed tracks. (Appendix II and Table V).

It also was discovered that some tracks were shorter and denser than common alpha particle tracks. These were regarded as tracks of particles with charge greater than two. Energy and momentum considerations make it possible to determine whether the particle was of charge two or greater. However, all doubtful tracks were assumed to be due to alpha particles. This assumption seems not unreasonable, considering the fact that the emission of alpha particles is much more probable than the emission of heavier particles, because of their lower threshold energies and Coulomb barrier heights.

In order to interpret~~e~~ the experimental observations and to assign reasonable reaction mechanisms, it was necessary to know the atomic composition of the emulsion. This, for type E1 emulsion as supplied by Ilford Limited, is shown in Table I.

The results for the single alpha-particle events are shown in Figure Ia in which the number of events in each 0.5 Mev interval is plotted as a function of energy. It is worth noting that the limit of resolution in this work is set, not ~~so much~~ only by the measurement of track length and particle energy, ~~as~~ but by the number of tracks measured.

EXPERIMENTAL RESULTS

Numbers of events found in 1.65 cm^2 in the plate are shown in Table II.

1. Single Track Events

Figure II shows a picture of a single alpha particle track observed in the plate. This was the most common event observed. These events are due to the ejection of alpha particles from silver and bromine nuclei which are the principal heavy nuclei present in the emulsion. Tracks of the recoiling residual nuclei were not observed in the emulsion, while they were observable in the case of the light elements emitting alpha particles.

The energy spectrum of alpha particles from silver and bromine nuclei is shown in Table III and Figure Ia. A total of 2693 alpha particle tracks is plotted as a function of energy in each 0.5 Mev interval, and the spectrum has also been corrected for the escape of alpha particles from the emulsion.

The energy spectrum shows two peaks, one at about 4.75 Mev and one at about 9.25 Mev.

Millar (19) calculated the alpha particle spectrum by the nuclear evaporation theory which is applicable to middle-weight nuclei excited by γ -rays. The theoretical energy spectrum for the plate exposed at maximum energy 24 Mev is shown in Figure Ib for the purpose of comparison with the experimental results. The theoretical curve is based on the assumption that simple (γ, α) reactions account for the majority of the alpha particle tracks observed. It will be noted that there is rough agreement between the observed and calculated higher energy peak as to peak position, and limit of particle energy. However, on the other hand, the theoretical curve shows few alpha particles with energy less than 6 Mev and therefore offers no explanation for the lower energy peak observed in the region 4 Mev to 5 Mev.

According to statistical theory, the higher energy peak will be attributed to alpha particles emitted in parallel and cascade reactions of the types (γ, α), ($\gamma, \alpha n$) and ($\gamma, \gamma'\alpha$), and the lower energy peak to threshold-favored cascade reactions of the types ($\gamma, \gamma'\alpha$), ($\gamma, n\alpha$) and ($\gamma, p\alpha$). The reactions ($\gamma, \alpha\alpha$) were observable as two-pronged alpha particle stars in this experiment, and therefore the events were classified as two track events. The energy spectrum does not show the secondary maxima between the two energy peaks as observed by Greenberg.

2. Two Track Events.

There were a considerable number of two track events which could not be regarded as due to the ejection of alpha particles from oxygen, nitrogen and carbon 13, and recoil of the residual nuclei. Both tracks showed two easily-identifiable alpha-particle tracks. These are probably due to the ejection of two alpha particles from silver and bromine.

Though the track of the recoiling nucleus was visible as a short stub at the origin of the alpha particle tracks, the number of these events observed would be dependent mainly on the person searching since the range of the recoiling nucleus is less than 2 microns. Also it was often difficult to distinguish between a bent single alpha particle track and an event which involved two alpha particles.

3. Three Track Events.

The disintegration of carbon into three alpha particles accounted for most of the three particle stars. When a carbon atom is excited by absorption of a photon it may be stabilized by emission of any of several particles. If an alpha particle is emitted the residual nucleus will be

Be^8, which may be in either the ground state or in an excited state. Be^8 is unstable and disintegrates with a very short lifetime into two alpha particles. On the other hand, a carbon nucleus may disintegrate into three alpha particles without passing through the intermediate Be^8 nucleus.

Of 736 observed stars 514 were tentatively identified as the reaction $C^{12}(\gamma,3\alpha)$ and 124 proceeded through an excited or ground state of Be^8. Figure III shows a picture of a typical carbon star which is probably due to the reaction as proceeding through the intermediate Be^8 nucleus. The longest alpha particle track proceeding outward from the centre is due to the first-emitted alpha particle and the narrow V-configuration is regarded as due to Be^8 break-up. If there was no V-configuration among the prongs, the star was attributed to the reaction which proceeds without passing through either an excited or ground state of Be^8.

For a number of stars the lengths and angles of the three prongs were measured. When the momenta of the prongs were added, the total momentum balance was shown to be zero with a very small correction for the photon momentum within the limit of error. The energy of the photon involved in the reaction was obtained by adding the kinetic energies of the three alpha particles and the binding energy of 7.15 Mev. (Appendix III),

There were a number of stars which did not show a momentum balance among the three prongs. This is probably the single stage three-body breakup of nitrogen described by the equation $N^{14}(\gamma, Li^6)\ 2\ He^4$. Figure IV shows a picture of such a nitrogen star, a Li^6 nucleus leaving a short stub in the emulsion.

4. Four Track Events.

There were 60 four pronged alpha particle stars, of which 37 were attributable to the reaction $O^{16}(\gamma,4\alpha)$ and 23 to the reaction $O^{16}(\gamma,2\alpha)Be^8$; $Be^8 \rightarrow 2\ He^4$. Figure V shows a picture of four-pronged oxygen stars due to the former reaction which exhibits no other obvious relation among the four prongs except conservation of linear momentum. However Figure VI shows the narrow V-configuration between two of four prongs which may be interpreted as due to the Be^8 breakup into two alpha particles.

The nitrogen four-pronged stars due to the reaction $N^{14}(\gamma, D)3He^4$ reported by Goward, and Millar and Cameron were not observed.

TABLE I

ATOMIC COMPOSITION OF ILFORD NUCLEAR RESEARCH EMULSTIO E1

Element	Ag	Br	I	C	H	O	N	S
$Gm/cm.^3$	1.85	1.34	0.052	0.272	0.056	0.266	0.067	0.010
Gm-atom/cc	0.0171	0.0167	0.00041	0.0226	0.056	0.0167	0.0048	0.00031

TABLE II

Numbers of Events found in 1.65 $cm.^2$ of The Plate E1(205)
Exposed at Maximum Betatron Energy 24 Mev.

Events	Numbers of Events/1.65 $cm.^2$
Single Track Events..................	2693
$Ag(\gamma, \alpha)Rh$	
$Br(\gamma, \alpha)As$	
Two Track Events.....................	58
Three Track Events....................	736
$C^{12}(\gamma, 3\alpha)$......................	514
$C^{12}(\gamma, \alpha)Be^8 \rightarrow 2\alpha$; $C^{12}(\gamma, \alpha)Be^{8*} \rightarrow 2\alpha$	124
$N^{14}(\gamma, Li^8)2He^4$	102
Four Track Events....................	60
$O^{16}(\gamma, 4\alpha)$..........	37
$O^{16}(\gamma, 2He^4)Be^8 \rightarrow 2\alpha$..........	23

TABLE III

Energy spectrum of single alpha particles found in 1.65 cm.^{2} of the plate El (205) exposed at maximum betatron energy 24 Mev. The spectrum has been corrected for the escape of alpha particles from the emulsion.

Energy Interval (Mev)		Intensity	Ce	Corrected Intensity
1.00 - 1.50		3		3.1
	1.40	3	1.021	3.1
1.50 - 2.00		8		8.2
	1.50	1	1.022	1.0
	.70	3	1.027	3.1
	.90	4	1.031	4.1
2.00 - 2.50		24		24.9
	2.00	4	1.033	4.1
	.20	4	1.038	4.2
	.30	6	1.040	6.2
	.40	10	1.041	10.4
2.50 - 3.00		62		65.2
	2.50	4	1.044	4.2
	.60	4	1.046	4.2
	.70	6	1.049	6.3
	.80	37	1.052	38.9
	.90	11	1.054	11.6
3.00 - 3.50		123		130.5
	3.00	11	1.056	11.6
	.10	16	1.059	16.9
	.20	52	1.061	55.2
	.30	22	1.064	23.4
	.40	22	1.066	23.4
3.50 -4.00		182		195.7
	3.50	48	1.069	51.2
	.60	20	1.072	21.4
	.70	28	1.075	30.2
	.80	25	1.078	27.0
	.90	61	1.080	65.9
4.00 - 4.50		261		285.0
	4.00	39	1.082	42.2
	.10	39	1.086	42.4
	.20	76	1.089	83.0
	.30	61	1.093	66.9
	.40	46	1.097	50.5
4.50 - 5.00		358		393.5
	4.50	103	1.100	113.0
	.60	67	1.102	74.0
	.70	49	1.106	54.3
	.80	102	1.109	111.0
	.90	37	1.113	41.2

TABLE III - CONTINUED

Energy Interval(Mev)		Intensity	Ce	Corrected Intensity
5.00 - 5.50		186		210.7
	5.00	39	1.116	45.4
	.10	56	1.120	62.7
	.20	30	1.123	33.8
	.30	38	1.124	42.8
	.40	23	1.131	26.0
5.50 - 6.00		149		170.6
	5.50	32	1.136	36.4
	.60	26	1.140	29.6
	.70	30	1.144	34.4
	.80	28	1.148	32.2
	.90	33	1.152	38.0
6.00 -6.50		127		148.0
	6.00	21	1.156	24.2
	.10	27	1.160	31.4
	.20	26	1.164	30.4
	.30	33	1.170	38.6
	.40	20	1.175	23.4
6.50 - 7.00		115		137.2
	6.50	25	1.180	29.5
	.60	24	1.184	28.4
	.70	16	1.190	19.0
	.80	28	1.195	33.5
	.90	22	1.214	26.8
7.00 - 7.50		113		136.1
	7.00	30	1.204	36.2
	.10	14	1.210	16.9
	.20	29	1.215	35.2
	.30	21	1.221	25.6
	.40	19	1.227	22.2
7.50 - 8.00		112		139.5
	7.50	29	1.234	35.8
	.60	18	1.240	22.4
	.70	31	1.246	38.6
	.80	13	1.252	16.3
	.90	21	1.259	26.4
8.00 - 8.50		96		122.5
	8.00	25	1.265	31.6
	.10	21	1.271	26.6
	.20	12	1.277	15.3
	.30	21	1.284	27.0
	.40	17	1.290	22.0

TABLE III - CONTINUED

Energy Interval (Mev)		Intensity	Ce	Corrected Intensity
8.50 - 9.00		108		139.9
	8.50	18	1.296	22.4
	.60	25	1.305	32.5
	.70	18	1.312	22.6
	.80	21	1.318	27.8
	.90	26	1.326	34.6
9.00 - 9.50		112		144.1
	9.00	27	1.333	36.0
	.10	31	1.341	41.6
	.20	24	1.348	32.4
	.30	18	1.354	24.4
	.40	12	1.360	16.3
9.50 - 10.0		89		123.5
	9.50	21	1.370	28.8
	.60	25	1.380	34.6
	.70	20	1.388	27.8
	.80	15	1.396	21.0
	.90	8	1.406	11.3
10.0 - 10.5		97		139.9
	10.0	19	1.415	27.8
	.1	14	1.423	19.8
	.2	18	1.431	25.8
	.3	26	1.442	37.5
	.4	20	1.452	29.0
10.5 - 11.0		70		103.6
	10.5	15	1.462	21.9
	.6	17	1.472	25.0
	.7	18	1.484	26.8
	.8	13	1.496	19.4
	.9	7	1.508	10.5
11.0 -11.5		54		83.2
	11.0	15	1.520	22.8
	.1	11	1.530	16.8
	.3	16	1.554	24.8
	.4	12	1.567	18.8
11.5 - 12.0		65		104.4
	11.5	10	1.574	15.7
	.6	16	1.591	25.4
	.7	10	1.605	16.1
	.8	17	1.619	27.6
	.9	12	1.633	19.6

TABLE III - CONTINUED

Energy Interval(Mev)		Intensity	Ce	Corrected Intensity
12.0 - 12.5		65		108.6
	12.0	25	1.647	41.2
	.1	6	1.651	9.9
	.2	10	1.675	16.8
	.3	15	1.691	25.4
	.4	9	1.710	15.3
12.5 - 13.0		38		67.1
	12.5	8	1.720	13.8
	.6	9	1.749	15.7
	.7	7	1.769	12.4
	.8	7	1.790	12.5
	.9	7	1.811	12.7
13.0 - 13.5		24		45.1
	13.0	5	1.831	9.2
	.1	5	1.853	9.3
	.2	1	1.875	1.9
	.3	12	1.900	22.8
	.4	1	1.925	1.9
13.5 - 14.0		26		51.8
	13.5	5	1.950	9.8
	.6	9	1.975	17.8
	.7	7	2.000	14.0
	.8	3	2.020	6.1
	.9	2	2.055	4.1
14.0 - 14.5		10		21.0
	14.0	3	2.085	6.3
	.1	4	2.116	8.2
	.2	2	2.147	4.3
	.3	1	2.181	2.2
14.5 - 15.0		3		6.9
	14.5	1	2.247	2.2
	.6	1	2.287	2.3
	.8	1	2.360	2.4
15.0 - 15.5		3		7.7
	15.0	1	2.447	2.4
	.1	1	2.504	2.5
	.4	1	2.675	2.8
15.5 - 16.0		3		8.7
	15.6	1	2.850	2.9
	.7	1	2.885	2.9
	.8	1	2.920	2.9
16.0 -16.5		2		6.2

TABLE III - CONTINUED

Energy Interval (Mev)		Intensity	Ce	Corrected Intensity
	16.1	2	3.104	6.2
16.5 - 17.0		3		10.8
	16.6	3	3.550	
17.0 - 17.5		1		1
18.5 - 19.0		1		1
Total Intensity		2693		3345

TABLE IV

RANGE-ENERGY RELATIONS FOR ALPHA PARTICLES IN ILFORD TYPE E1 EMULSIONS

R * range in microns
E = energy in Mev.

R → ↓ E →	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0	0.00	0.01	0.02	0.03	0.04	0.05	0.07	0.08	0.10	0.12
1	0.15	0.18	0.21	0.24	0.27	0.30	0.34	0.38	0.42	0.45
2	0.49	0.52	0.55	0.58	0.62	0.65	0.68	0.72	0.76	0.80
3	0.84	0.87	0.91	0.95	0.99	1.03	1.07	1.10	1.14	1.18
4	1.21	1.24	1.27	1.31	1.35	1.38	1.42	1.46	1.49	1.53
5	1.56	1.59	1.62	1.66	1.70	1.73	1.76	1.79	1.83	1.86
6	1.89	1.93	1.96	1.99	2.02	2.04	2.07	2.11	2.14	2.17
7	2.20	2.23	2.26	2.28	2.31	2.34	2.37	2.39	2.42	2.45
8	2.48	2.50	2.53	2.55	2.58	2.60	2.63	2.66	2.68	2.72
9	2.74	2.76	2.78	2.81	2.84	2.86	2.88	2.92	2.94	2.96
10	2.98	3.01	3.03	3.05	3.07	3.10	3.12	3.15	3.17	3.20
11	3.22	3.25	3.27	3.29	3.32	3.34	3.37	3.39	3.41	3.43
12	3.46	3.48	3.50	3.52	3.54	3.56	3.58	3.61	3.63	3.65
13	3.67	3.70	3.72	3.74	3.76	3.78	3.80	3.82	3.84	3.86
14	3.88	3.91	3.93	3.95	3.97	3.99	4.01	4.03	4.05	4.07
15	4.09	4.11	4.13	4.15	4.17	4.19	4.21	4.23	4.25	4.27
16	4.29	4.31	4.33	4.35	4.37	4.39	4.41	4.43	4.45	4.47
17	4.48	4.50	4.51	4.53	4.55	4.57	4.58	4.60	4.62	4.64
18	4.66	4.67	4.69	4.71	4.73	4.75	4.77	4.78	4.80	4.82
19	4.84	4.85	4.87	4.89	4.91	4.93	4.95	4.96	4.98	5.00
20	5.02	5.03	5.05	5.07	5.08	5.10	5.12	5.13	5.15	5.17

TABLE IV - CONTINUED

R ↓ E ↘	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
21	5.18	5.20	5.22	5.23	5.25	5.27	5.28	5.30	5.32	5.33
22	5.35	5.37	5.38	5.40	5.42	5.43	5.45	5.47	5.48	5.50
23	5.52	5.53	5.55	5.57	5.58	5.60	5.62	5.63	5.65	5.67
24	5.68	5.70	5.72	5.73	5.75	5.77	5.78	5.80	5.82	5.83
25	5.85	5.87	5.88	5.90	5.92	5.93	5.95	5.97	5.98	6.00
26	6.02	6.03	6.05	6.07	6.08	6,10	6.11	6.13	6.14	6.16
27	6.17	6.19	6.20	6.22	6.23	6.25	6.27	6.28	6.30	6.31
28	6.33	6.34	6.36	6.37	6.39	6.40	6.42	6.43	6.45	6.47
29	6.48	6.50	6.51	6.53	6.54	6.56	6.57	6.59	6.60	6.61
30	6.63	6.64	6.66	6.67	6.69	6.70	6.71	6.73	6.74	6.76
31	6.77	6.69	6.80	6.81	6.83	6.84	6.86	6.87	6.89	6.90
32	6.91	6.93	6.94	6.96	6.97	6.99	7.00	7.01	7.03	7.04
33	7.05	7.06	7.08	7.09	7.10	7.11	7.13	7.14	7.16	7.17
34	7.19	7.20	7.21	7.23	7.24	7.25	7.26	7.28	7.29	7.30
35	7.31	7.33	7.34	7.36	7.37	7.39	7.40	7.41	7.43	7.44
36	7.45	7.46	7.48	7.49	7.50	7.51	7.53	7.54	7.55	7.56
37	7.58	7.59	7.60	7.61	7.63	7.64	7.66	7.67	7.69	7.70
38	7.71	7.73	7.74	7.75	7.76	7.78	7.79	7.80	7.81	7.83
39	7.84	7.86	7.87	7.89	7.90	7.91	7.93	7.94	7.95	7.96
40	7.98	7.99	8.00	8.01	8.03	8.04	8.05	8.06	8.08	8.09
41	8.10	8.11	8.13	8.14	8.16	8.17	8.19	8.20	8.21	8.23
42	8.24	8.25	8.26	8.28	8.29	8.30	8.31	8.33	8.34	8.36
43	8.37	8.39	8.40	8.41	8.43	8.44	8.45	8.46	8.48	8.49

TABLE IV - CONTINUED

R ↓ E →	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
44	8.50	8.51	8.53	8.54	8.55	8.56	8.58	8.59	8.60	8.61
45	8.63	8.64	8.65	8.66	8.68	8.69	8.70	8.71	8.73	8.74
46	8.75	8.76	8.78	8.79	8.80	8.81	8.83	8.84	8.85	8.86
47	8.88	8.89	8.90	8.91	8.93	8.94	8.95	8.96	8.98	8.99
48	9.00	9.01	9.02	9.03	9.04	9.06	9.07	9.08	9.09	9.10
49	9.11	9.13	9.14	9.15	9.16	9.18	9.19	9.20	9.21	9.22
50	9.23	9.24	9.26	9.27	9.28	9.29	9.30	9.31	9.33	9.34
51	9.35	9.36	9.38	9.39	9.40	9.41	9.42	9.43	9.44	9.46
52	9.47	9.48	9.49	9.50	9.51	9.53	9.54	9.55	9.56	9.58
53	9.59	9.60	9.61	9.63	9.64	9.65	9.66	9.68	9.69	9.70
54	9.71	9.73	9.74	9.75	9.76	9.78	9.79	9.80	9.81	9.83
55	9.84	9.85	9.86	9.88	9.89	9.90	9.91	9.93	9.94	9.95

R	E	R	E	R	E	R	E
56	10.0	66	11.0	76	12.1	86	12.9
57	10.1	67	11.1	77	12.2	87	13.0
58	10.2	68	11.3	78	12.3	88	13.0
59	10.3	69	11.4	79	12.3	89	13.1
60	10.4	70	11.5	80	12.4	90	13.2
61	10.5	71	11.6	81	12.5	91	13.3
62	10.6	72	11.7	82	12.6	92	13.3
63	10.7	73	11.8	83	12.6	93	13.4
64	10.8	74	11.9	84	12.7	94	13.5
65	10.9	75	12.0	85	12.8	95	13.6

TABLE IV - CONTINUED

R	E	R	E	R	E	R	E
96	13.7	105	14.3	130	16.1	155	17.7
97	13.7	110	14.75	135	16.4	160	18.0
98	13.8	115	15.1	140	16.7	165	18.3
99	13.9	120	15.4	145	17.1	170	18.6
100	14.0	125	15.75	150	17.4		

TABLE V

ESCAPE CORRECTION FACTOR FOR SINGLE ALPHA PARTICLES TRACKS (C_e)

$$C_e = \left[1 - \frac{L}{2(t - 4)} \right]^{-1} ,$$

where t= emulsion thickness in microns*
L= track length in microns

E → ↓ C_e	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
1	1.017	1.018	1.019	1.020	1.021	1.022	1.023	1.027	1.029	1.031
2	1.033	1.036	1.038	1.040	1.041	1.044	1.046	1.049	1.052	1.054
3	1.056	1.059	1.061	1.064	1.066	1.069	1.072	1.075	1.078	1.080
4	1.082	1.086	1.089	1.093	1.097	1.100	1.102	1.106	1.109	1.113
5	1.116	1.120	1.123	1.124	1.131	1.136	1.140	1.144	1.148	1.152
6	1.156	1.160	1.164	1.170	1.175	1.180	1.184	1.190	1.195	1.214
7	1.204	1.210	1.215	1.221	1.227	1.234	1.240	1.246	1.252	1.259
8	1.265	1.271	1.277	1.284	1.290	1.298	1.305	1.312	1.318	1.326
9	1.333	1.341	1.348	1.354	1.360	1.370	1.380	1.388	1.396	1.406
10	1.415	1.423	1.431	1.442	1.452	1.462	1.472	1.484	1.496	1.508
11	1.520	1.530	1.540	1.554	1.567	1.574	1.591	1.605	1.619	1.633
12	1.647	1.651	1.675	1.691	1.710	1.720	1.749	1.769	1.790	1.811
13	1.831	1.853	1.875	1.900	1.925	1.950	1.975	2.000	2.020	2.055
14	2.085	2.116	2.147	2.181	2.207	2.247	2.287	2.324	2.360	2.404
15	2.447	2.504	2.560	2.618	2.675	2.763	2.850	2.885	2.920	2.980
16	3.039	3.104	3.169	3.275	3.380	3.465	3.550	3.663	3.785	3.922

* t = 100 microns in the case of the plate used in this work.

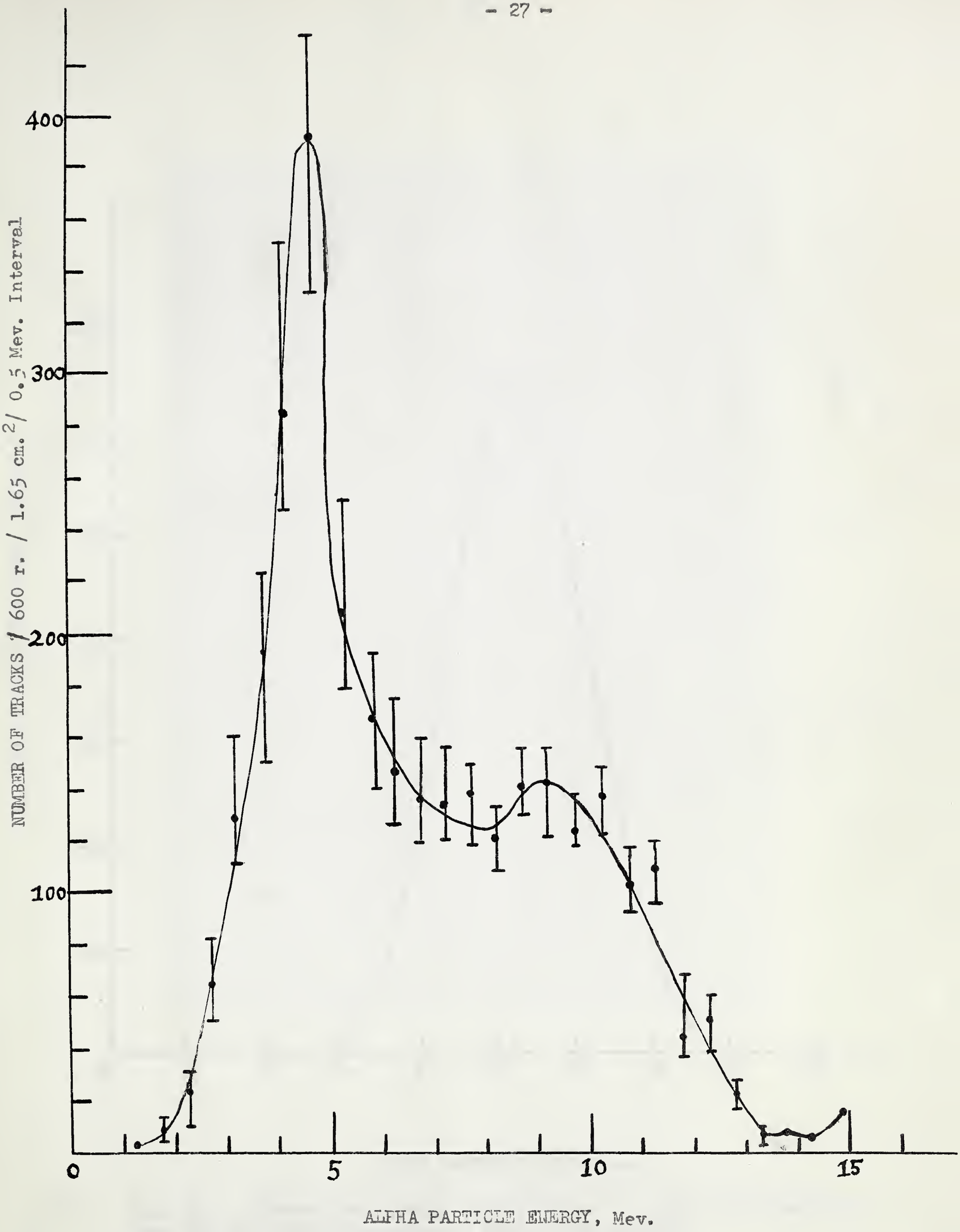

Fig. Ia. Energy spectrum of single alpha particles resulting from the photonuclear reaction of silver and bromine nuclei found in 1.65 cm.^{2} of plate El (205) irradiated at maximum betatron energy 24 Mev. The spectrum has been corrected for the escape of alpha particles from the emulsion.

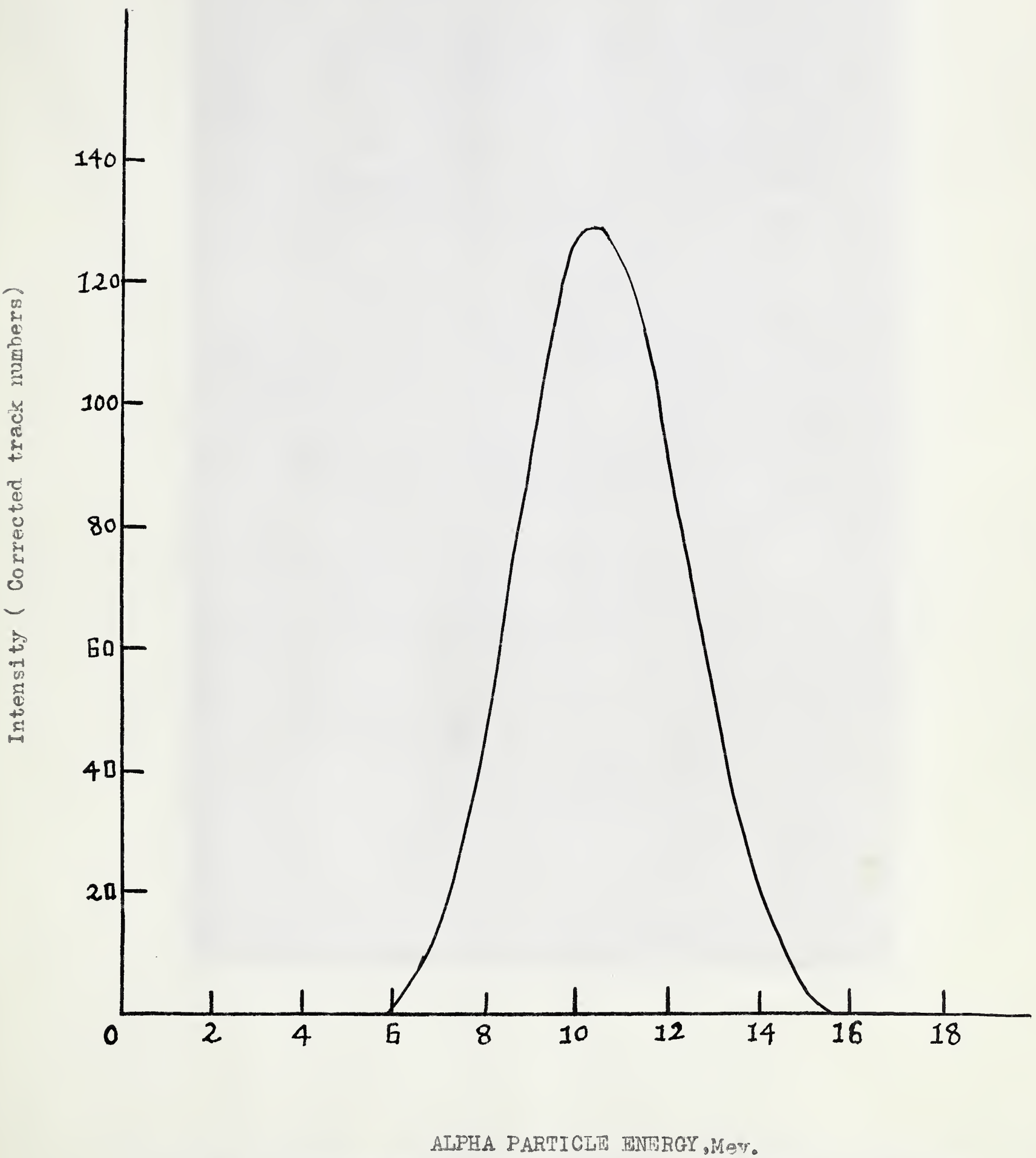

Fig. Ib. Theoretical energy distribution of single alpha particles from the photo-disintegration of silver and bromine.

Fig. II. Photograph of a single alpha particle track due to the photo-disintegration of silver and bromine nuclei, i.e., Ag(γ, α) Rh & Br(γ , α)As

Fig. III Photograph of a carbon star, due to the reaction $C^{12}(\gamma, \alpha)Be^8 \rightarrow 2He^4$ or $C^{12}(\gamma, \alpha)Be^{8*} \rightarrow 2\,He^4$. The longest alpha particle track is due to the first-emitted alpha particle. There is a momentum balance among three prongs.

Fig. IV. Photograph of a star, probably due to the reaction $N^{14}(\gamma, Li^8)2\,He^4$.

A short stub is from a Li^8 nucleus.

Fig. V. Photograph of an oxygen star due to the reaction $O^{16}(\gamma, 4\alpha)$.
There is a momentum balance among the prongs.

Fig. VI. Photograph of an oxygen star due to the reaction $O^{16}(\gamma, Be^8)2He^4$. The typical V-configuration of the alpha-particles from the breakup of the ground state Be^8 is visible. This event is known as birdfoot.

DISCUSSION.

This examination of a nuclear research emulsion irradiated at maximum betatron energy 24 Mev has revealed all the possible reactions involving the emission of alpha particles in all major constituents of the emulsion.

The double-peaked alpha particle energy spectrum resulting from the photo-disintegration of silver and bromine has been studied. The lower energy peak has been considered as arising from threshold-favored alpha-particle emission in reactions of the types $(\gamma, \gamma'\alpha)$, $(\gamma, n\alpha)$ and $(\gamma, p\alpha)$. The higher energy peak has been considered as arising from parallel and cascade reactions principally of the types (γ, α), $(\gamma, \alpha n)$ and $(\gamma, \gamma'\alpha)$. However, the more precise interpretation of these events could have been deduced in terms of the statistical theory of nuclear reactions, if the general features of the cross-section curves had been obtained.

For a few photonuclear reactions, such as $C^{12}(\gamma, \alpha)Be^8 \rightarrow 2He^4$ and $O^{16}(\gamma, 4\alpha)$, an irradiation at a single energy setting of the betatron is sufficient to determine reaction cross sections as a function of photon energy, since the energies of all the disintegration products may be determined separately for each event. This procedure cannot be applied to photonuclear reactions of silver and bromine nuclei, since in these cases the alpha-particles are followed or are accompanied by gamma-rays, protons or neutrons, which have not been recorded in this experiment. It is necessary to determine the yield of alpha-particles as a function of bremsstrahlung energy by means of the photon difference method (20) in order to obtain the photo-alpha cross-section curves. Lack of information on the cross-section curves has made the interpretations highly speculative.

The energy distribution of single alpha particles did not show the secondary maxima in the region above 6 Mev as observed by Greenberg.

The events occurring in light nuclei are distinguishable from those in silver and bromine. However, if a 4 or 5 Mev alpha-particle track originates

from an oxygen or nitrogen nucleus, the track of the recoiling nucleus would have a range of less than 2 microns and might easily be misinterpreted by the observer. Therefore some of the low energy particles included in the observed spectrum may have originated from light nuclei in the emulsion.

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APPENDIX I

Calculation of Range and Energy.

The high concentration of silver and bromine in nuclear research emulsions causes a considerable reduction in their thickness after fixation, when the unused silver is removed. If the ratio between the thickness of the emulsion before and after processing, which is called shrinkage factor, is known, it is possible to correct for this effect in determining track lengths by using the formula

$$R = \left[Y^2 + (SZ)^2\right]^{\frac{1}{2}}$$

where R = the original track length (before processing)

Y = horizontal component of a track (after processing)

Z = vertical component of a track (after processing).

S = shrinkage factor.

The horizontal component of a track was measured by means of a micrometer disc attached to the microscope eyepiece and the vertical component of a track was measured by the vertical movement of the microscope tube. The shrinkage factor 2.63 was used for this particular plate.

The shrinkage factor of an emulsion may be determined in the following way: The plate is exposed to a nearly point source of alpha-particles at a distance, D, from the emulsion. The position of the track with respect to the position of the source determines the angle of the tracks. The horizontal and vertical components of a track in the developed emulsion are measured (ℓ and d respectively) and the distances L and D are obtained. (Figure VII. A plot of ℓ/d against L for several tracks yields a straight line if S is constant, and the value of S may be determined from the slope of the line.

The theoretical range-energy relationship for protons in air was computed by Livingston and Bethe (21), and Smith (22). From this relationship for protons the range-energy relationship for alpha-particles in air was determined by Webb (23). These relationships may be applied to nuclear emulsions by multiplying the range values by the stopping power of the emulsion relative to air.

The range-energy relationship for proton and alpha particles has also been determined experimentally by a number of investigators. Lattes, Fowler and Cueer (24), and Bradner et al. (25) have published the most comprehensive results. The former workers employed Ilford type B1 emulsions and the latter C2 emulsions in their work. Cameron altered the values of the former workers by 3% to take into account the greater stopping power of El emulsions. This relationship was re-examined before adopting it in this experiment.

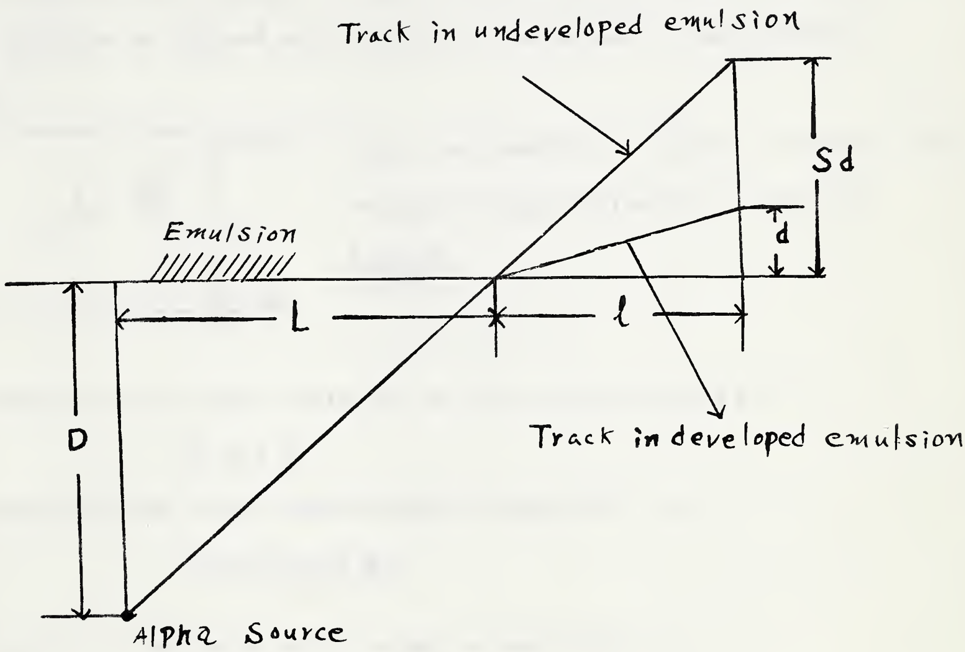
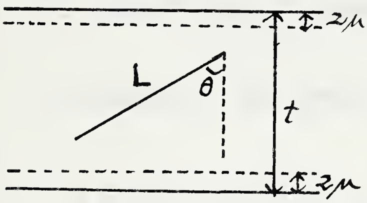


Fig. VII Diagram showing a method of determining the shrinkage factor for an emulsion.

APPENDIX II

Calculation of Escape Correction Factor

Consider an emulsion of thickness t microns, and assume that single alpha particle tracks of length L microns are randomly oriented in the emulsion at angle θ with respect to the normal to the emulsion surface



Then, the fraction of tracks of length L that escape at angle θ from the emulsion is

$$\frac{L \cos \theta}{(t - 4)} ,$$

The fraction of the tracks contained in solid angle $2\pi \sin\theta \, d\theta$ is

$$\sin \theta \, d \theta .$$

The fraction of the tracks which escape at angle θ is

$$\frac{L \cos \theta \sin\theta \, d\theta}{(t - 4)}$$

The fraction of the tracks which escape at any angle is

$$\int_0^{\frac{\pi}{2}} \frac{L\cos \theta \sin\theta \, d\theta}{(t - 4)} = \frac{L}{2 (t - 4)}$$

Therefore the escape correction factor by which the observed number of tracks of length L within the emulsion must be multiplied in order to obtain the total number of tracks which originate in the emulsion is given by

$$C_e = \left[1 - \frac{L}{2 (t - 4)} \right]^{-1}$$

APPENDIX III

<u>Identification of the momentum balance among the three prongs of a carbon star.</u>

Consider a particle of mass 3m which breaks into three equal particles each of mass m, of momenta $\vec{P}_1$, $\vec{P}_2$ and $\vec{P}_3$, and of energies E_1, E_2 and E_3.

$$P = \sqrt{2mE}$$

By conservation of momentum $\vec{P}_1 + \vec{P}_2 + \vec{P}_3 = 0$.

The energy of the photon involved in the reaction is given by

$$h\nu = E_1 + E_2 + E_3 + \text{ the binding energy.}$$

<u>Example:</u>

A carbon star in a single plane located at (21.2: 121.5: 7.0)

	Range in μ	Energy in Mev
1	12.7	3.61
2	4.23	1.27
3	5.64	1.76

$$h\nu = 3.61 + 1.27 + 1.76 + 7.15 = 13.8 \text{ Mev}$$

$$P_1 = \sqrt{2 \times 4 \times 3.61} = \sqrt{28.88} = 5.38.$$

$$P_2 = \sqrt{2 \times 4 \times 1.27} = \sqrt{10.16} = 3.18$$

$$P_3 = \sqrt{2 \times 4 \times 1.76} = \sqrt{14.08} = 3.76$$

$$P_x = -\ 5.38 \cos 83 - 3.18 \cos 50 + 3.76 \cos 44$$

$$= -\ 0.645 - 2.04 + 2.70$$

$$= +\ 0.01$$

$$P_y = 5.38 \sin 83 - 3.18 \sin 50 - 3.76 \sin 44$$

$$= 5.34 - 2.44 - 2.61$$

$$= 0.33$$